Advanced OPC Mask-3D and Resist-3D modeling

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The objective of this paper is to extend the ability of a more stable overall process control for the 28 nm Metal layer. A method to better control complex 2D-layout structures for this node is described. Challenges are coming from the fact that the structures, which limit the process window are mainly of 2D routing nature and are difficult to monitor. Within the framework of this study the emphasis is on how to predict these process-window-limiting structures upfront, to identify root causes and to assist in easier monitoring solutions enhancing the process control.

To address those challenges, the first step is the construction of a reliable Mask-3D and Resist-3D model. Advanced 3D-modeling allows better prediction of process variation upfront. Furthermore it allows highlighting critical structures impacted by either best-focus shifts or by low-contrast resist-imaging effects, which then will be transferred non-linearly after etch.

This paper has a tight attention on measuring the 3D nature of the resist profiles by multiple experimental techniques such as Cross-section scanning electron microscopy methods (X-SEM) and atomic force microscopy (AFM). Based on these measurements the most reliable data are selected to calibrate full-chip Resist-3D model with. Current results show efficient profile matching among the calibrated R3D model, wafer AFM and X-SEM measurements. In parallel this study enables the application of a new metric as result of the resist profiles behavior in function of exposure dose. In addition it renders the importance on the resist shape. Together these items are reflected to be efficient support on process optimization and improvement on the process control.

Keywords: Mask-3D, Resist-3D, Profile sensitivity to dose, Resist profile

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1. Introduction

The challenge posed to photolithography (for 28 nm and beyond technology nodes) is to further enhance the overall process window for the most critical layers that implies increasingly important process control. One of the most critical layers to pattern is the 28 nm Metal layer, on which this study is based on. The complexity is caused by the fact that its most problematic layouts are usually dense 2D structures with low image contrast, which on top of that are difficult to monitor. Therefore, the upfront prediction of structures limiting the lithography process window (PW) becomes crucial and requires tight attention.

The challenge of the PW hotspot determination can be covered by defectivity analysis using Process Window Qualification (PWQ) flow. The PWQ flow is a well-established wafer inspection method coupled with design based binning algorithm in order to determine lithographic critical structures PW within lithography dose and focus matrices. For metal layers it is done "After Etch Inspection "(AEI) and the "Chemical Mechanical Planarization" (CMP) step.

The problematic is subsequent to the application of the PWQ flow. We observed a mismatch between overlapping simulated PW and the PWQ analysis. One of the key metrics of PWQ is usable-depth-of-focus (uDoF); we found 30 nm delta uDoF, whereas PW expectations based on a model with 2D-approximations of a flat mask and photoresist yielded wider. The reason of the mismatch between PWQ and PW might come either from unpredicted behavior in lithography or from unpredicted behavior in etching and/or CMP. Because this study relies on the capabilities of computational lithography, our approach investigates more on any current limitations of lithography and its models. We concentrated our attention to two major factors: one is the best-focus shift between patterns while the other is the changing resist profile.

Currently a thin-mask approximation is the most widely applied method to model the photo-mask part of the lithographic model. This is called the Kirchhoff approximation, which considers the mask thickness to be infinitely thin. Such a 2D approach would only take best-focus shifts caused by resist and underlying stack into account, but not the part caused by the mask [1][2]. The pattern dependent best-focus shift cannot be accurately predicted by currently used thin-mask approximation. Figure 1 (simulation results by M3D) illustrates clearly that the best-focus vs. pitch, is not constant as a thin mask model would predict.

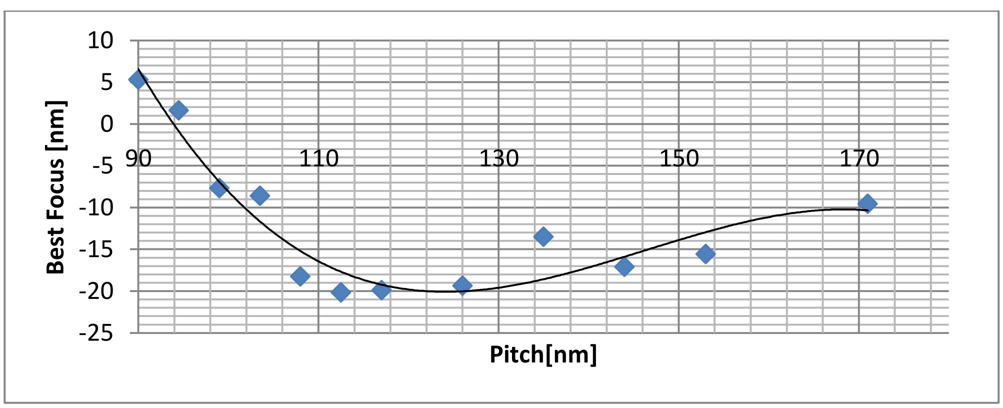


Figure 1: Best-focus through pitch (Annular illumination, 1.35NA) representing the pattern dependent best-focus shift w M3D

Accordingly the 3-dimensional nature of the mask needs to be taken into account via a mask-3D (M3D) model, which is therefore thought to become indispensable to build an accurate model.

The second factor is the comportment of resist profiles. For instance resist with significant top loss may be etched away during the etching step and reveal the to-be-protected region of certain features to etchant. Furthermore a non-optimized resist sidewall angle (SWA) may lead to undesired etch bias and cause the after etch feature to deviate from the design target. In consequence to solve these critical issues, computational lithographic applications need to take the resist profile

information into consideration. Hence, the full-chip lithography model that these applications are based on is required to have the capability of predicting 3D resist profiles.

Therefore the main objective of this work is the construction of a reliable Mask-3D model, and Resist-3D model in order to achieve a more accurate predictability of the process variations. In parallel we attended to assist the determination of root causes in processing and end-product logic layout styles that can result in easier monitoring methods to make improvements on the process control.

2. Results and Calibration

The wafer exposure including data for the calibration dataset was carried out using an ASML NXT:1950i scanner (4X reduction immersion lithography exposure system with a wavelength λ=193 nm and numerical aperture NA=1.35) on C28 metal layer. For the modeling calibration and PW determinations on layout, the Tachyon computational lithography platform was applied.

The setup gauge set for the reference model included CD-SEM data consisting of 1D and 2D features representative at best condition and through process window. Subsequently the model was expanded to comprise mask-3D effects by the generation of M3D library suitable for Resist-3D baseline model. Finally the baseline model was completed with resist profile data in order to achieve the calibrated R3D.

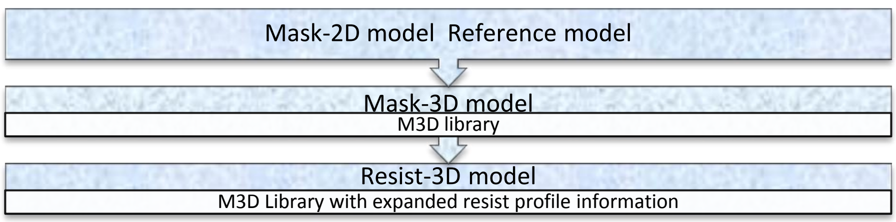


Table 1: Overview of simplified flow of modeling

2.1 The Mask-3D model

The main purpose of Mask-3D modeling came from the fact that there is an important interaction of the 3D nature of the mask with the designed pattern reflecting in best-focus shift offset. Thus we had the intention to capture a larger scope of pattern dependent best focus variation introduced by mask topography with M3D model than with a thin mask model.

By an accuracy check of the calibrated M3D – Figure 2 (here below) illustrate clearly that the M3D model captures wider range of mask topography related best focus shift than the thin mask (Flat M2D) model.

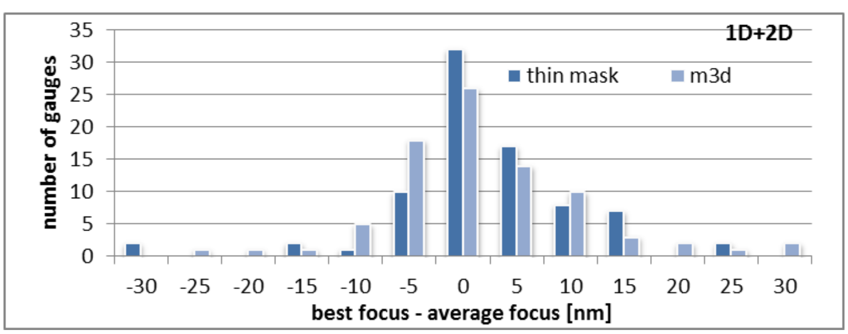


Figure 2: Average Best Focus for a given number of gauges including 1D and 2D patterns

Note that the average of the Best Focus is similar: -105.3nm of M3D model vs. -107.8nm of thin mask model (-105nm on wafer). Despite of the Best Focus average proximity of the two models, M3D reveals more physical - proved

furthermore by the fact that M3D resulted in smaller simulated overlapping process window (PW closer to wafer) due to pattern dependent best focus shift.

Overall the above calibrated M3D model enabled proper detection of the focus shift and the created M3D library served as input data (CD-SEM) for the following R3D calibration.

2.2 Calibration of the Resist-3D model

The purpose of the R3D model was to enable efficient prediction of the resist profiles of all layout patterns at varying focus and dose conditions. Such that the best possible wafer exposure methods and OPC correction strategies can be determined to avoid profile-induced hotspots. In parallel R3D model can be applied to predict resist contour at different resist height to estimate side-wall angles and top-loss.

2.2.1 The resist-3D model

For a well-calibrated Tachyon FEM+ model, a combination of the mask model and optical model is used to describe the physical behavior of the exposure stage in lithography. The final resist profile is the overall computation of the light's field and intensity distribution plus the resist development effect in 3D. A conventional OPC model including Tachyon FEM+ After Development Inspection (ADI) model simulates the resist development effects in 2D. The R3D model computes the 3D resist profile by accounting for physical effects. The model captures both the diffusion effects in the Z-direction (perpendicular to the wafer) from the post exposure bake (PEB) stage as well as surface interaction effects from the development stage to accurately predict the resist profiles.

The formulation of the R3D model is characterized as a linear approximation to the 3D physical resist model. It consists of a series of terms that are linearly combined to approximate the resist process. The expressions of these terms are determined by examining the analytical solutions to the physical resist model under some special conditions. Together with the existing 2D diffusion terms, the R3D model can represent the 3D resist diffusion during post bake process. The R3D model describes the acid concentration deviation from aerial image intensity due to surface effects. Since Photo-acid generator (PAG) distribution before exposure has a z- dependency, the acid diffusion at resist top and bottom is no longer isotropic. Surface effects (e.g., surface contamination at top and/or bottom resist interface) sometime play an important role in determining resist top loss and/or bottom footing. These effects are modeled empirically by introducing a z- dependent scaling and/or addition to the initial acid distribution produced by exposure. For example, the z-dependent addition is modeled by a function that reaches the maximum magnitude when z is at the resist surface and approaches zero when z is well inside the resist [3].

So the R3D model calibration is an extension of conventional FEM+ ADI (2D) model calibration platform. The calibration flow relied on the previously generated M3D Library served as bottom CD data providing our baseline model. Then the R3D model was fitted with resist profile data. Since the model calibration platform requires CD measurements as input, resist profile information needed to be converted into several measurement groups. Such a group should be measured at the same resist height.

2.2.2 Preparation of the Resist Profile data

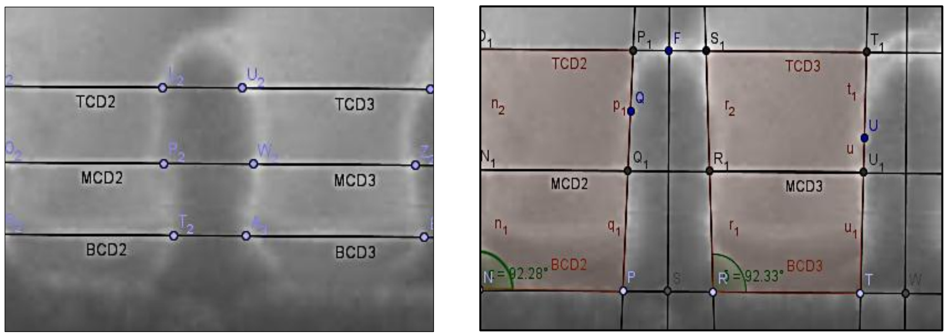
In order to achieve relevant and reliable resist profile information at the nanometer level for the calibration of a R3D model, we assessed that this profile information would need to be delivered by combined metrology techniques: Cross-section scanning electron microscopy methods (X-SEM) and 3D atomic force microscopy (AFM3D).

Cross Section-SEM data

For the X-SEM measurements we focused on pitch 90 nm pattern. Note that the well-defined sampling is a limiting factor for this technique, which need tight attention. Thus this method becomes complicated or impossible for critical structures. Samples were cleaved from a Focus Exposure Matrix (FEM) wafer. The set of samples included X-sections at overall three different focus and six different dose conditions.

Different approaches were used for the data treatment in order to have a more clear idea of the real space CD since the resist lines are not identical and do not have orderly shapes such as symmetrical trapezoids. Furthermore, in the direction perpendicular to the X-section plane a roughness of the lines is observed. Note that the extraction of the cross section SEM can lead to a pronounced uncertainty because of the absence of any possible automated treatment. Within this work two "visual" methods were applied for data treatment (see Figure 3):

(a) Exact Profile Fitting– measurements following the profile curvature of the resist with additional averaging on a set of measured trenches within pattern
(b) Trapezoid Fitting – measurements by additional trapezoid contour on the resist profile with additional averaging on a set of measured trenches within pattern



(a) (b)

Figure 3: X-SEM data treatment examples by (a) Exact Profile fitting (b) Trapezoid Fitting

AFM data

The AFM measurements data set consisted of isolated trench, pitch 120 nm and pitch 200 nm patterns through three focus conditions and three dose conditions (trenches were measured). Note that due to tool limitation coming from tip dimension pitch 90 nm could not be measured.

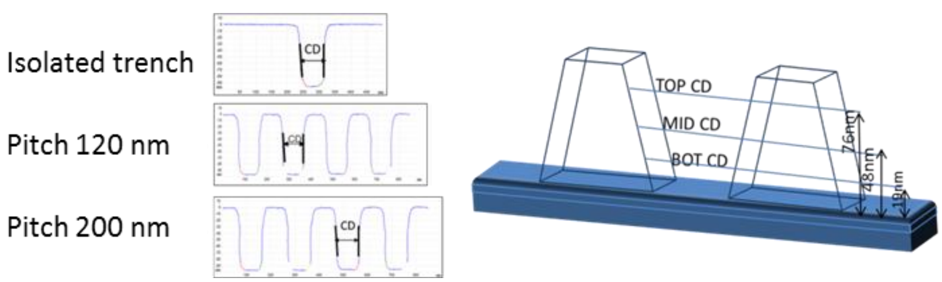


Figure 4: AFM3D measured patterns – isolated trench, pitch 120 nm and pitch 200 nm and the illustration of CD acquirement

In order to convert the obtained profile information into CD information, the top-middle-bottom CD are measured systematically at 80% (top), 50% (middle) and 20% (bottom) of the resist height as indicated on Figure 4.

These measured AFM profiles show clear and low-noise signals from which CD values (at bottom, mid and top of the resist) can be extracted fairly easily. So according to these measurement findings we predominantly used AFM3D data as source of input for the R3D model-calibration. The X-Section-SEM data and images are used for verification purposes.

2.2.3 The R3D gauge construction

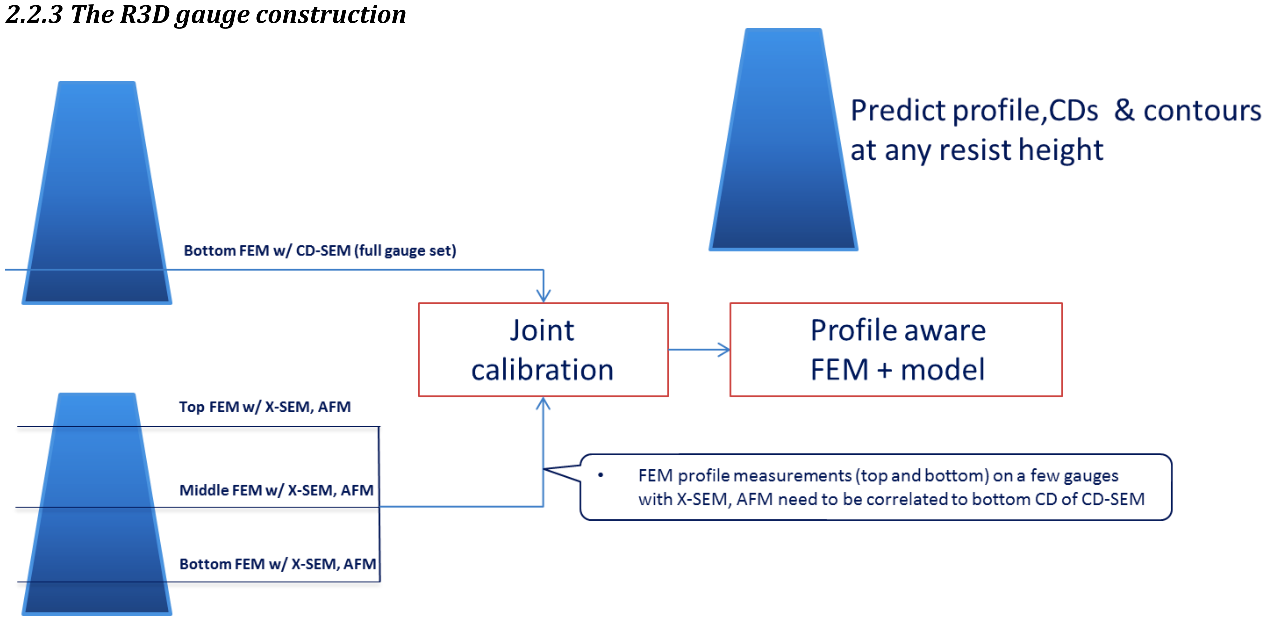
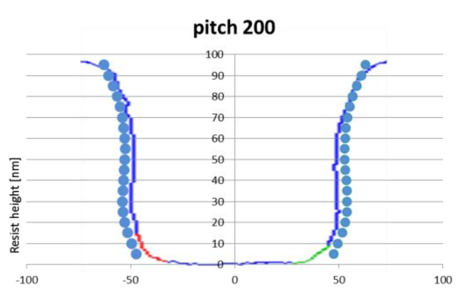


Figure 5: Data preparation flow for R3D gauge building

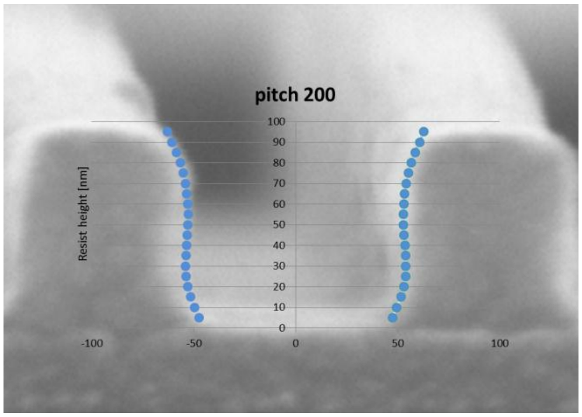
Figure 5 shows the flow of R3D gauge construction for the R3D model calibration. Once the R3D gauge was constructed it was used to calibrate R3D model. Together with defocus and dose, resist height was used as a PW space dimension. Optimization was done using linear solver to minimize CD RMS.

As described in the data preparation step, the bottom AFM CD was biased toward the baseline model CD. Therefore, the top and middle wafer CDs are the effective fitting data in final R3D model calibration. Throughout the calibration the attention was pointed on profile fit. Figure 6 shows the simulated profile of pitch 200 nm overlaid with AFM CD and with cross-section SEM. Both resulted in well matching profile fit.

With the R3D model, we can also predict the resist profile of pitch 90 nm pattern and overlay it with X-SEM. As shown in Figure 7, the predicted resist profile had excellent matching with the X-SEM measurement. The R3D model not only matches the profile shape but also accurately predicts the resist loss (~30 nm) observed on wafer.



(a)



(b)

Figure 6: Resist profile for pitch 200nm illustrating the matching between (a) Wafer AFM profile *solid line* vs. R3D model *filled dots* (b) Cross section SEM vs. R3D model *filled dots*

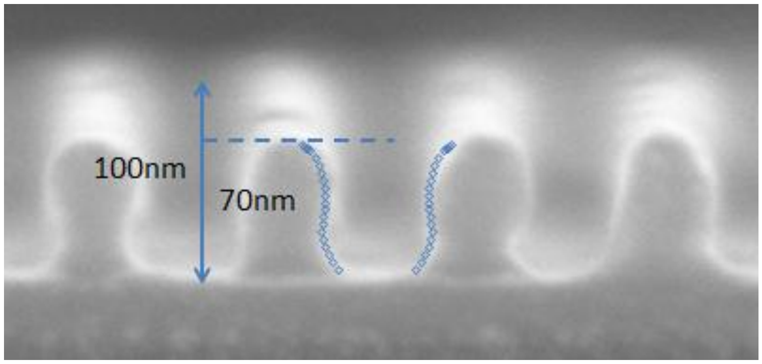


Figure 7. Tachyon R3D model profile overlaid with X-SEM for pitch 90 pattern. Original resist thickness = 100 nm resist loss = 30 nm.

2.2.4 Hotspot detection capability of the calibrated R3D

Using Tachyon LMC (Lithography Manufacturing Check) with the calibrated R3D, weak points were highlighted in term of strong resist slope effects. Those hotspots were highlighted first as results of Process Window Qualification (PWQ) analysis. Furthermore they were identified as most critical patterns by the usage of appropriate CD detector settings on a small clip verification run with R3D model at the top of the resist. Note that LMC without 3D effects did not detect these patterns as critical structures.

Table 2 shows an example for LMC (with R3D) validation on one of the most critical hotspots vs. defectivity SEM after etch and CMP. The Resist-3D model resulted in good matching with the defectivity.

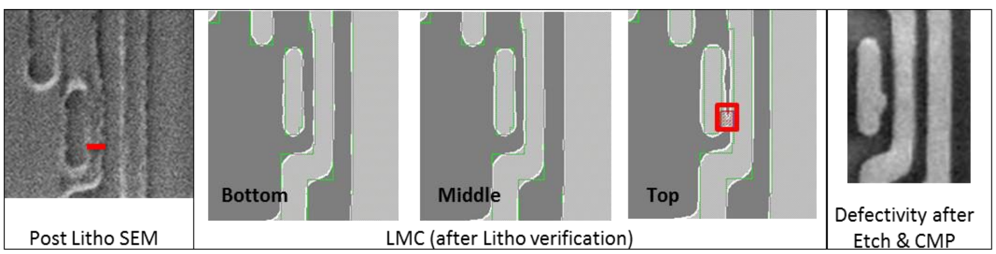


Table 2: LMC validation on hotspots representing the simulated contour at bottom-middle-top resists height vs. post lithography CD SEM images vs. Defectivity after etch & CMP (at edge of process window)

2.2.5 Discussion on failure mechanism

The profile sensitivity to dose

The data collection for the calibration emphasized the relevance of the resist profile by mean that the profile is not constant through dose. First from scatterometry data we identified the sensitivity of the profile ΔCD/ΔDose to dose referring to different comportments of top-middle-bottom line CD through dose (see Figure 8).

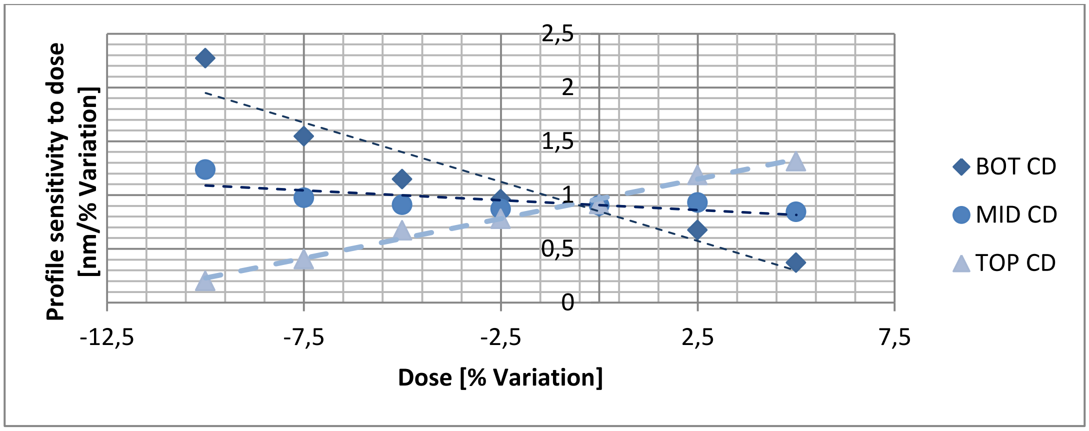


Figure 8: Scatterometry top-middle-bottom line CD data for pitch 90 nm pattern

Subsequently the identified tendency has also been proofed by physics [5] and has been confirmed by metrology data set used for calibration. We found matching comportment of the top, middle and bottom CD behavior on AFM3D data set. The integration of X-SEM data into that discussion is more complex coming from the fact that the resist lines, as seen on obtained images, do not have regular shapes. In spite of that X-SEM data merely reveals a slight tendency with identified resist profile comportment through dose.

For verification purpose of that behavior through dose the calibrated R3D was applied on pitch 90 (line CD) vs. the Hotspot 1, found as a good candidate for representing one of the most critical structures. The R3D simulation results (see Figure 9.), focusing on contour at the top and bottom resist height, illustrates clearly the importance of the top loss effect. That might bring forth the fact that the sensitivity is twice more pronounced for highlighted critical structure than for the 1D pitch 90 nm. At nominal dose the model already predicts top loss for the hotspot. Indeed that can be the root cause of the gap between the simulated PW (post lithography) and PWQ.

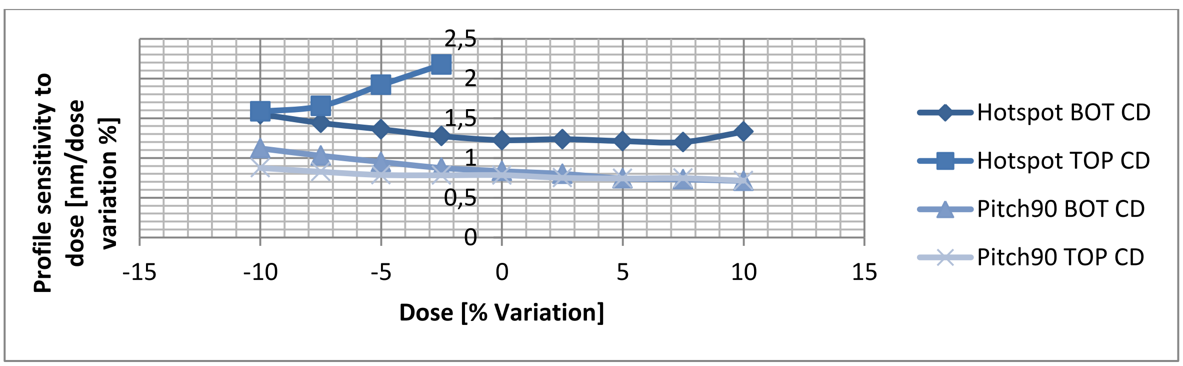


Figure 9 :Resist profile sensitivity through dose of pitch 90 nm (note “line” data are plotted) vs. hotspot at nominal focus

After reviewing these results on CD through dose, it is clear that with the knowledge of the profile sensitivity ΔCD/ΔDose through dose, the accuracy of the prediction can be improved. In parallel it can lead to enhancement of process control.

The resist shape

Subsequently the cross section SEM provided data on pitch 90 nm showed “bump-shaped” (see Figure 10) resist lines that revealed the importance of the awareness of the profile.

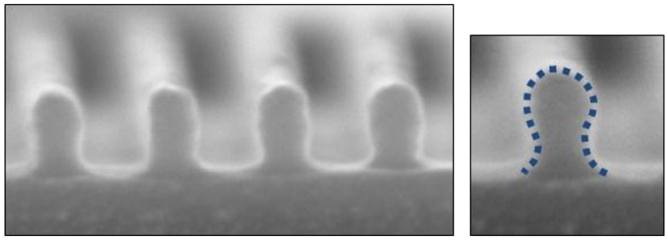


Figure 10: Cross section SEM examples for “bump-shaped” resist profile

In consequence that the resist shape is strongly related to contrast variation to dose therefore the contrast variation anticipates the changing SWA through dose [5]. Means if we can achieve better contrast average it would result in less variation across the stack. Moreover due to the standing waves impact, oscillations might occur through the resist height.

Tachyon R3D model was confirmed to be efficient to provide exact information on resist’s profile - without metrology constraints (Figure 7) – so it can be used to reflect on these process limitations. Thus the R3D model can be applied as a support for better understanding the root-cause behind the resist shape. Also this provided data can be a helpful indicator/metric for further enhancements.

Accordingly, a methodology including R3D simulation and then mitigation can be efficient to make improvements on the process capability: such as improvement on illumination using source optimization assisted by R3D or amelioration on stack reflectivity.

3. Conclusion

Within the framework of this paper, the ultimate goal was sharpened on the achievement of a more accurate upfront predictability of the most critical 2D patterns. For that purpose, a calibration methodology of mask-3D and resist-3D model has been overviewed and discussed. According to obtained results, mask topography and resist profile aware OPC model came in front.

A new analysis metrics, the resist profile sensitivity to dose, was identified during the calibration enabling pronounced enhancement on hotspot detection. Furthermore along the R3D model benefits, we have demonstrated that it is an efficient support to improve on process for future nodes. So the above-mentioned items became key points for further improvement in capability and robustness of process monitoring.

4. Acknowledgement

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